The ATLAS Leptonic-Z Excess from Light Squark Productions in the NMSSM Extension with a Heavy Dirac Gluino

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The ATLAS Collaboration announced a 3σ excess in the leptonic-$Z + jets + \not{E}_T$ channel. We show that such an excess can be interpreted in the extension of the Next-to-Minimal Supersymmetric Standard Model (NMSSM) with a heavy Dirac gluino and light squarks. The abundant Z bosons can be produced by light squark pair productions with the subsequent decays $\tilde{q} \to q\tilde{\chi}_2^0 \to qZ\tilde{\chi}_1^0$. We investigate the relevant parameter space by considering the constraints from both the ATLAS and CMS direct SUSY searches. Our model can provide sufficient Z-signal events in large parameter space if only the ATLAS searches are considered. After combining the ATLAS and CMS searches, the maximal number of signal events can still reach about 15, which is within the 1σ region of the observed excess. For comparison, we study the conventional low energy NMSSM with a Majorana gluino and its maximal number of signal events are about 11, although we cannot realize such model in the known supersymmetry breaking scenarios.

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I. INTRODUCTION

With the discovery of a 125 GeV Standard Model (SM)-like Higgs boson [1, 2], all the SM particles have already been found, and the main goal of the LHC experiment switches to search for physics beyond the SM (BSM). As we know, supersymmetry (SUSY) is still the best-motivated framework. It provides an elegant solution to gauge hierarchy problem, achieves gauge coupling unification at a high scale, and naturally has the lightest supersymmetric particle (LSP) as a dark matter candidate if R parity is preserved. However, the current null results of SUSY searches from the LHC together with the measured 125 GeV Higgs mass have placed stringent exclusion limits on the parameter space of its simplest realization: the Minimal Supersymmetric Standard Model (MSSM) [3]. Thus, it is worth to consider seriously the possible extensions of MSSM, such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and its extensions.

Meanwhile, several recently observed excess of signal events may have already given us the new physics clues. Notably, the ATLAS Collaboration reported a 3σ excess in the channel of two same-flavour opposite-sign dileptons with an invariant mass around Z boson 81 GeV $< m_{\ell^+\ell^-} <$ 101 GeV, jets, and missing transverse energy $\not{E}_T$ [4]. The goal of this search is to probe two scenarios

- The gluino $\tilde{g}$ pair productions and the following two-step decays through sleptons to the LSP neutralino $\tilde{\chi}_1^0$, which leads to the off-Z dileptons.
- The general gauge mediation (GGM), where gluinos first via 3-body decay into quark pairs and neutralino $\tilde{\chi}_1^0$, and the latter then decay into a very light gravitino $\tilde{G}$ plus a Z boson, which results in on-Z dileptons.

At the 8 TeV LHC with an integrated luminosity of 20.3 fb^{-1}, the observed number of leptonic-Z events for combined electron and muon channels is 29 while 10.6 ± 3.2 events are expected in the SM [4], which corresponds to 3σ deviation. On the other hand, the CMS Collaboration has also implemented similar search [5] and no significant signal on Z excess was observed. The maximal deviation was found 2.6σ in the dilepton mass window 20GeV $< m_{\ell^+\ell^-} <$ 70GeV.

Several solutions to explain this excess for both SUSY [6–15] and non-SUSY models [16] have been proposed. Most of SUSY interpretations are based on gluino/squark pair production processes, which can be summarized as follows

- The MSSM with GGM [7], the Z-signal can be produced via decay chain $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \to q\bar{q}Z\tilde{G}$, where the first step decay through an off-shell squark exchange.
- The MSSM with a light right-handed sbottom $\tilde{b}_1$, a bino-like LSP $\tilde{\chi}_1^0$ and nearly degenerated higgsino-like next-to-LSP (NLSPs) $\tilde{\chi}_{2,3}^0$ [8]. In this scenario, corresponding decay chain is $\tilde{g} \to b\tilde{b}_1^\dagger \to b\bar{b}\tilde{\chi}_{2,3}^0 \to b\bar{b}\tilde{\chi}_1^0 Z$. However, such rich b signals are tightly constrained by b-jet searches.
- The MSSM with a tunned spectrum, i.e., light squraks $\tilde{q} \sim 500 - 750$ GeV, bino-like NLSP $\tilde{\chi}_3^0 \sim 350$ GeV and higgsino-like LSPs $\tilde{\chi}_{1,2}^0 \sim 150 - 200$ GeV. The corresponding decay chain is $\tilde{q} \to q\tilde{\chi}_3^0 \to q\tilde{\chi}_{1,2}^0 Z$ [9].
- The MSSM with a split spectrum, the gluinos decay into higgsino-like NLSPs through t-$\tilde{t}_1$-loop, followed by higgsinos decay into the bino LSP plus Z boson, i.e., $\tilde{g} \to g\tilde{\chi}_{2,3}^0 \to g\tilde{\chi}_1^0 Z$ [10].
- The MSSM with mixed stops [11], the Z boson can be produced by heavy stop decay, $\tilde{t}_2 \to Z\tilde{t}_1$, where the light stop has a mass close to the LSP in order to evade the LHC search constraints.
- The goldstini model with gauge mediated SUSY breaking scenario [12], in which they also considered gluino radiative decay into higgsino-like neutralino $\tilde{g} \to g\tilde{\chi}_{1,2}^0$. The difference is there exists a pseudo-goldstino G' in the spectrum which leads to $\tilde{\chi}_{1,2}^0 \to ZG'$.
- Finally, the NMSSM with a singlino-like LSP $\tilde{\chi}_1^0$ and a bino-like NLSP $\tilde{\chi}_2^0$ [13–15], where extra Z bosons can be produced through $\tilde{g} \to q\bar{q}\tilde{\chi}_2^0 \to q\bar{q}Z\tilde{\chi}_1^0$ or $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\chi}_1^0 Z$.

In the explanation using light squarks [9, 15], the Majorana gluino mass was chosen by hand to be heavy at low energy scale. However, we cannot realize such scenario in the UV completion of the MSSM/NMSSM for the known supersymmetry breaking mechanisms since the squark masses will be driven to the order of gluino mass due to the renormalization group equation running (For an example, see Ref. [17].). In this work, we investigate an extension of the NMSSM with a Dirac gluino, which provides a UV completion of the above scenario. In particular, the heavy Dirac gluino will not induce the SUSY electroweak fine-tuning problem, and then such extension is still natural [18–58]. We demonstrate the leptonic-Z excess can be successfully explained through light squark pair productions.

Before studying the model in details, we would like to discuss the decay patterns of the first two generation squarks in the context of the MSSM and explain our strategy to address the Z excess. With heavy gluino, squarks decay

into quarks plus neutralino/chargino: $\tilde{q} \to q\tilde{\chi}_i^0$ or $\tilde{q} \to q'\tilde{\chi}_i^{\pm}$. The decay channel $\tilde{q} \to q\tilde{\chi}_1^0$ is always kinematically favored and for right-handed squarks it can be dominant since in most case $\tilde{\chi}_1^0$ is bino-like. However, the left-handed squarks strongly prefer to decay into the wino-like charginos/neutralinos due to large squark-quark-wino couplings. Moreover, squarks decay into higgsino-like charginos/neutralinos are only important for the third generation squarks in which squark-quark-higgsino couplings are sizeable because of large Yukawa couplings. Due to these properties, when the LSP neutralino is bino-like, the NLSP neutralino is wino-like (higgsino-like), squarks can not have large branching ratio for cascade decay $\tilde{q} \to q\tilde{\chi}_2^0(\tilde{\chi}_{2,3}^0) \to q\tilde{\chi}_1^0 Z$. While in case of the bino-like NLSP and higgsino-like LSP, one may potentially has considerable branching ratio for above cascade decays but the specific fine-tuning of the mass spectrum is required. Unfortunately, above situation is also true for the MSSM with a Dirac gluino. So we pay our attention to the NMSSM with the Dirac gluino. In this case the LSP (NLSP) neutralino is singlino-like (bino-like) and both $\tilde{q} \to q\tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ can have large branching ratios in large parameter space.

This work is organized as follows. In Section II, we present our model and demonstrate its key features. In Section III, we describe the cutflow of the ATLAS search for the leptonic-Z+$jets$+$\not{E}_T$ signal and give the corresponding best fit benchmark points. We scan the relevant SUSY parameter space to study the capability of our model in interpreting the ATLAS Z-peaked excess by considering the constraints from both the ATLAS and CMS SUSY searches. As a comparison, we also discuss the same signal channel in the usual NMSSM within the same parameter space. Finally, our conclusion is given in Section IV.

II. THE NMSSM EXTENSION WITH A HEAVY DIRAC GLUINO AND LIGHT SQUARKS

Dirac gauginos have been proposed decades ago [18–20], and recently have been studied extensively in model building and phenomenology [21–58]. The SUSY models with Dirac gluinos have notable advantages comparing with their Majorana counterparts. Firstly, they have special renormalization properties, the so-called supersoft behavior [21–23, 41, 44] which allows specific mass spectra where squarks are much lighter than glunio. Secondly, some subprocesses involved in the first two generations of squarks pair productions vanish (those final states with squarks of the same chirality) since the t-channel Dirac gluino exchange cannot mediate the chirality-flip processes. This leads to the reduction of squark pair production cross sections in Dirac case compared to the Majorana case, which will significantly alleviate their bounds from the current LHC direct SUSY searches, especially in the heavier Dirac gluino region ($M_{\tilde{g}} \gtrsim 2-3$ TeV) [42, 43, 48, 49]. This is known as supersafe behavior and play a crucial role when using our model to explain the ATLAS Z-peaked excess. In terms of supersafe, the first and second generations of squarks can be as light as 700 GeV, which actually removes the constraints as we want. Therefore, the appropriate and convenient framework for weak scale SUSY is the unification of Dirac gluinos and semi-soft SUSY breaking. In order to generate the Dirac gluino mass, we need to introduce a chiral superfield Φ with $SU(3)_C \times SU(2)_L \times U(1)_Y$ quantum number $(\mathbf{8},\mathbf{1},\mathbf{0})$.

In this paper, we consider the general NMSSM framework whose superpotential is given by [59]

$$W = Y_u Q H_u \bar{u} - Y_d Q H_d \bar{d} - Y_e L H_d \bar{e} + (\mu + \lambda S) H_u \cdot H_d + \xi_F S + \frac{1}{2}\mu' S^2 + \frac{1}{3}\kappa S^3, \tag{1}$$

where $Q,\ \bar{u},\ \bar{d},\ L,\ \bar{e}$, and S are the NMSSM chiral superfields, λ and κ are the dimensionless Yukawa couplings, μ and μ' are the bilinear mass terms, and ξ_F is the tadpole term. The corresponding SUSY breaking soft terms are

$$\begin{aligned} -\mathcal{L}_{soft} = &\, T_u Q H_u \bar{u} - T_d Q H_d \bar{d} - T_e L H_d \bar{e} + T_\lambda H_u \cdot H_d S + \frac{1}{3} T_\kappa S^3 + B_\mu H_u \cdot H_d + \frac{1}{2} m_S'^2 S^2 + \xi_S S + h.c. \\ &+ m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + m_Q^2 |Q^2| + m_L^2 |L^2| + m_{\bar{u}}^2 |\bar{u}^2| + m_{\bar{d}}^2 |\bar{d}^2| + m_{\bar{e}}^2 |\bar{e}^2| \\ &+ M_1 BB + M_2 WW + M_3 GG + M_D^B B\tilde{S} + M_D^G G\Phi + h.c., \end{aligned} \tag{2}$$

where $T_{u,d,e,\lambda,\kappa}$ are the trilinear soft terms, $B_\mu, m_S'^2$ are the bilinear soft terms, $M_{1,2,3}$ are respectively the soft Majorana gaugino masses for bino, wino and gluino, as well as the Dirac type of gluino (bino) mass M_D^G (M_D^B). Noticed that in Eq. 2, one could has mixed mass gluino eigenstates, i.e., pseudo-Dirac gluino, while the pure Dirac or Majorana gluino corresponds to $M_3 = 0$ or $M_D^G = 0$. For simplicity, we consider the pure Dirac gluino and set $M_3 = M_D^B = 0$.

In Fig. 1, we show the total cross sections of the first two generation squark pair productions ($\tilde{q}\tilde{q} + \tilde{q}\tilde{q}^* + \tilde{q}^*\tilde{q}^*$) at the 8 TeV LHC. For comparison, the NLO+NLL cross section of Majorana gluino pair production based on `NLL-fast` [60] calculation is also presented. We find that the cross sections of total squark pair productions are larger than 10 fb for $m_{\tilde{q}} \lesssim 900$ GeV. Without taking into account cut efficiency and branching ratio suppression in each step of squark cascade decay chain, we may obtain sufficient Z events in this mass region. The crucial point is then how to keep the

Z yield in squark cascade decays and escape the constraints from the ATLAS and CMS direct SUSY searches. To achieve this goal, we consider the following strategy

- The neutralino sector is similar to that of Refs. [13, 14], i.e., the bino-like NLSP $\tilde{\chi}_2^0$ and singlino-like LSP $\tilde{\chi}_1^0$. By choosing $M_2 \sim \mu \gg M_1$, the branching ratios of squark decays into wino and Higgsino are suppressed. As a consequence, the branching ratio of squark decay into bino is almost 100%.
- For simplicity, we assume slepton $\tilde{\ell}$ and the third generation squarks $\tilde{t}_{1,2}/\tilde{b}_{1,2}$ are decoupled. Also, to keep the nice feature of heavy Dirac gluino model, gluino mass is fixed at $m_{\tilde{g}} \gtrsim 2.6$ TeV.
- The mass splitting between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is taken to be $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq 100$ GeV to forbid $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ decay, which guarantees $\mathrm{Br}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) \sim 100\%$ [1].

In the next section, we present our simulation results for both Z excess signal events and LHC constraints.

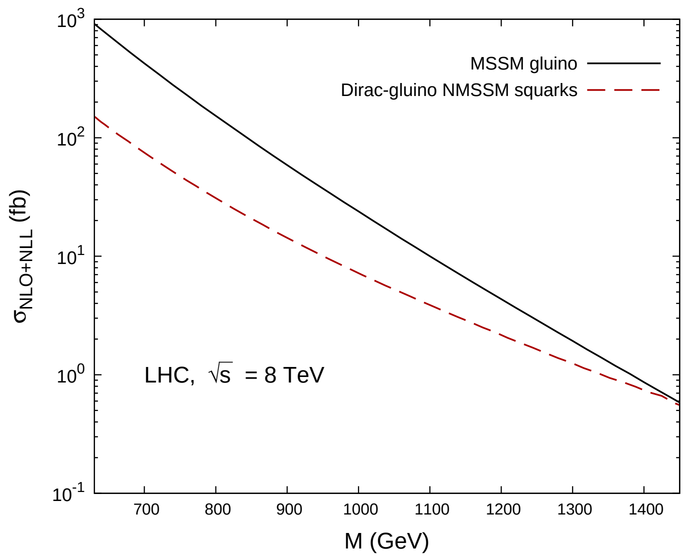

FIG. 1: The total NLO+NLL cross section of squark pair productions $\sigma_{NLO+NLL} = \sigma(\tilde{q}\tilde{q} + \tilde{q}\tilde{q}^* + \tilde{q}^*\tilde{q}^*)$ in our model at the 8 TeV LHC (red dashed line). For comparison, the NLO+NLL cross section of gluino pair production for decoupled squarks is also shown (black solid line).

III. THE Z-PEAKED EXCESS AND LHC SUSY SEARCH CONSTRAINTS

For the purpose of studying collider phenomenology, we implement the model in the Mathematica package `SARAH`[61], which generates `SPheno`[62] output file to calculate the particle mass spectra, mixing matrices as well as the low energy constraints. It can also create the corresponding `UFO`[63] model file which can be used by `MG5_aMC` [64]. In our simulation, the parton level events are generated by `MG5_aMC`, whose output `LHE` file then feeds into `Pythia8` [65] to implement particle decays, parton showering and hadronization [2], and the package `NLL-fast` is used to calculate the NLO+NLL k-factor of the squark pair productions. Moreover, we use `Delphes3` [67] for fast detector simulation.

The ATLAS and CMS Collaborations have carried out copious SUSY searches at the LHC. The null signals for most of the searches so far have put quite stringent bounds on many SUSY models. As a result, those scenarios, which could potentially explain the Z boson excess, may have already been excluded. In order to use the LHC SUSY searches to constrain our interesting models, we use a private package in which most of the current LHC SUSY searches have been recasted. The package was first used in Ref. [68] and further developed in Refs. [69, 70]. The check of validation can be found therein as well.

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[1] This can also be realized by choosing specific SUSY parameters such that the coupling $h\bar{\tilde{\chi}}_1^0\tilde{\chi}_2^0$ is suppressed.

[2] In order to employ `Pythia8` to correctly handle the decays of all SUSY particles in our model, we use the so-called "semi-internal processes" which was introduced in Ref. [66].

Specifying to our current work, we find that the LHC searches for the final states with jets and $\not{E}_T$ and with [5, 71] and without [72, 73] isolated leptons are related to the searches for the final states with on-shell Z boson [74]. We recast those searches by strictly following the analyses in the corresponding conference notes or published papers. The Delphes with default ATLAS setup is used for fast detector simulation.

In order to measure whether a model is excluded by the current LHC searches or not, we define variables $R^i \equiv \frac{N^i_{\rm NP}}{N^i_{\rm UP}}$, where the $N^i_{\rm NP}$ and $N^i_{\rm UP}$ are the numbers of new physics event and upper limit in each signal region S_i for a given analysis, respectively. The largest $R^{\rm max} = \max_i(R^i)$ among all signal regions of all relevant searches is specified to the corresponding model. As a result, $R^{\rm max} > 1$ means that there is at least one signal region in which the number of signal events is larger than the upper limit of current data, so this model is excluded. In the LHC analyses, the ATLAS Collaboration has explicitly given $N^i_{\rm UP}$ for each signal region, while the CMS Collaboration only presented the observed numbers of events and corresponding background events and its uncertainty. We calculate the 95% *C.L.* $N^i_{\rm UP}$ for the CMS analyses via standard Bayesian procedure as follows

$$\frac{1}{\mathcal{N}}\int_0^{N_{\rm UP}} \mathcal{L}(n_{obs}|N_s, N_b, \sigma_b)P(N_s)dN_s = 0.95, \tag{3}$$

where $P(N_s)$ is uniform prior probability and $\mathcal{N} = \int_0^\infty \mathcal{L}(n_{obs}|N_s, N_b, \sigma_b)P(N_s)dN_s$ is a normalization factor. Assuming Gaussian distribution for background and signal uncertainties, the likelihood function in Eq. 3 can be written as

$$\mathcal{L}(n_{obs}|N_s, N_b, \sigma_b) = \frac{1}{\sqrt{2\pi\sigma_s^2}\sqrt{2\pi\sigma_b^2}}\int_{-5\sigma_s}^{5\sigma_s} ds \int_{-5\sigma_b}^{5\sigma_b} dbP(n_{obs};\mu)e^{\frac{db^2}{2\sigma_b^2}}e^{\frac{ds^2}{2\sigma_s^2}} . \tag{4}$$

Practically, the probability function $P(n_{obs};\mu)$ is taken as Possion distribution $\mu^{n_{obs}}e^{-\mu}/n_{obs}!$ for $n_{obs} \leqslant 100$ while taken as Gaussian distribution $e^{(n_{obs}-\mu)^2/2\mu}/\sqrt{2\pi\mu}$ for $n_{obs} > 100$. Here, the expectation value $\mu = N_s + ds + N_b + db$, and the signal error $\sigma_s = 0.01\ n_s$. We find the derived $N^i_{\rm UP}$ from Eq. (3) will not change much as long as the signal uncertainty is within a few tens of percent. The calculated $N^i_{\rm UP}$s for all signal regions in Ref. [5] are shown in Table I for illustration.

TABLE I: The 95% *C.L.* $N^i_{\rm UP}$ for all signal regions in the CMS search for events with two leptons, jets, and missing transverse momentum [5].

$N_{\rm jets}$	≥ 2			≥ 3		
$E_T^{\rm miss}$ (GeV)	$100-200$	$200-300$	>300	$100-200$	$200-300$	>300
Total background	1204 ± 106	74.5 ± 11.3	12.8 ± 4.3	478 ± 43	39.2 ± 6.6	5.3 ± 2.3
Data	1187	65	7	490	35	6
$N_{\rm UP}$	211	23.2	8.6	107	16.5	8.9

With these necessary tools, we are able to apply relevant LHC SUSY search constraints on all benchmark models. We now briefly describe the cuts flow of the ATLAS analysis on Z excess. According to the search, the signal events should satisfy the following requirements

1. Events contain at least two same-flavour opposite-sign leptons.
2. The leading lepton $p_T^{\ell,1} > 25$ GeV and sub-leading lepton $p_T^{\ell,2} > 10$ GeV.
3. The invariant mass of these two leptons must fall into Z boson mass window $81 < m_{\ell^+\ell^-} < 101$ GeV.
4. Events further have ≥ 2 jets with $p_T^j > 35$ GeV and $|\eta| < 2.5$.
5. The missing transverse energy $\not{E}_T > 225$ GeV.
6. $H_T > 600$ GeV with $H_T \equiv p_T^{\ell,1} + p_T^{\ell,2} + \sum_i p_T^{j,i}$.
7. $\Delta\phi(j_{1,2}, \not{E}_T) > 0.4$, where $\Delta\phi$ is the azimuthal angle between two objects in parenthesis.

In Table II, we present the most relevant information for two benchmark points. Their cut efficiency, survival number of signal events in the ATLAS cut flow as well as the corresponding $R^{\rm max}$ values are shown in Table III. From this table, we find that **bench1** can give the best fit signal events (18.7) and satisfy all of the ATLAS constraints we have considered, but not the CMS constraints. While **bench2** can escape the constraints form both the ATLAS

and CMS searches. As the price, the signal events drop to 14.2, which roughly corresponds to 2σ deviation from the SM and is within 1σ region of the observed excess. Finally, Fig. 2 shows the H_T and $\not{E}_T$ distributions respectively for two benchmark points after applying all cut selections in the ATLAS cut flow except the H_T and $\not{E}_T$ cuts. Some important features can be learnt from here

- From Table III, we find that H_T and $\not{E}_T$ cuts are crucial in the cut flow, and hard H_T and $\not{E}_T$ distributions are required in order to keep sufficient survival events.
- As shown from Table II and Fig. 2, **bench2** has relatively compressed spectrum which leads to softer H_T and $\not{E}_T$ distributions compared with **bench1**.

As a consequence, **bench2** is easier to evade the constraints from the LHC searches especially when the CMS limits are taken into account. Meanwhile, fewer events can pass H_T and $\not{E}_T$ cuts in the ATLAS leptonic-$Z + jets + \not{E}_T$ search. On the other hand, **bench1** easily satisfies the requirement of Z-signal events but is challenged by the CMS constraints.

TABLE II: The relevant particle masses, branching ratios, and NLO+NLL cross sections for two benchmark points of our model.

	$M_{\tilde{q}^{1,2}_{L,R}}$	$M_{\tilde{\chi}^0_1}$	$M_{\tilde{\chi}^0_2}$	M_h	$\mathrm{Br}(\tilde{q}_{L,R} \to q\tilde{\chi}^0_2)$	$\mathrm{Br}(\tilde{\chi}^0_2 \to Z\tilde{\chi}^0_1)$	$\sigma_{\mathrm{NLO+NLL}}$ (fb)
bench1	693	283	398	125	100%	95.7%	79
bench2	642	313	428	125	100%	95.6%	133

TABLE III: The cut efficiency and signal events for our model in the ATLAS cut flow at the 8 TeV LHC with luminosity $\mathcal{L} = 20.3$ fb^{-1}. The $R^{\max}$ values are also presented for the ATLAS searches alone as well as for both the ATLAS and CMS searches.

	All Events	Cut1	Cut2	Cut3	Cut4	Cut5	Cut6	Cut7	N_{Sig}	$R^{\max}_{\mathrm{ATLAS}}$	$R^{\max}_{\mathrm{ATLAS+CMS}}$
bench1	10^5	3869	3839	3549	3482	1599	1252	1165	18.7	0.56	1.26
bench2	10^5	3851	3822	3530	3441	996	574	528	14.2	0.52	0.96

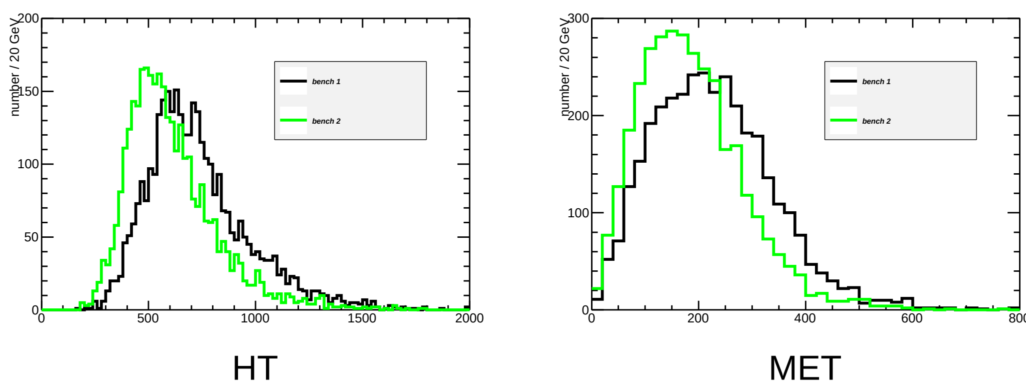

FIG. 2: H_T (left) and $\not{E}_T$ (right) distributions after implementing the ATLAS cut flow, except the cuts on H_T and $\not{E}_T$. The **bench1** and **bench2** are plotted by black and green solid lines, respectively.

We further implement a grid scan in the $m_{\tilde{q}} - m_{\chi^0_2}$ plane. Contours of signal events and corresponding exclusion limits are shown in Fig. 3. Among all searches undertaken in this study, we find that the CMS search for final states with jets, $\not{E}_T$ and two opposite-sign same-flavor leptons at the Z pole [5] gives the most stringent bound on most of the models that could explain the ATLAS excess because of the similar signature they are looking for. The exclusion curves in Fig. 3 are shown with (blue curve marked as ATLAS+CMS) and without (green curve marked as ATLAS)

the CMS constraint, respectively. From the figure, we conclude that after taking into account all the current LHC SUSY searches, our model can give at most ~ 15 events for the ATLAS Z-peaked excess, which means the excess can be addressed within 1σ level.

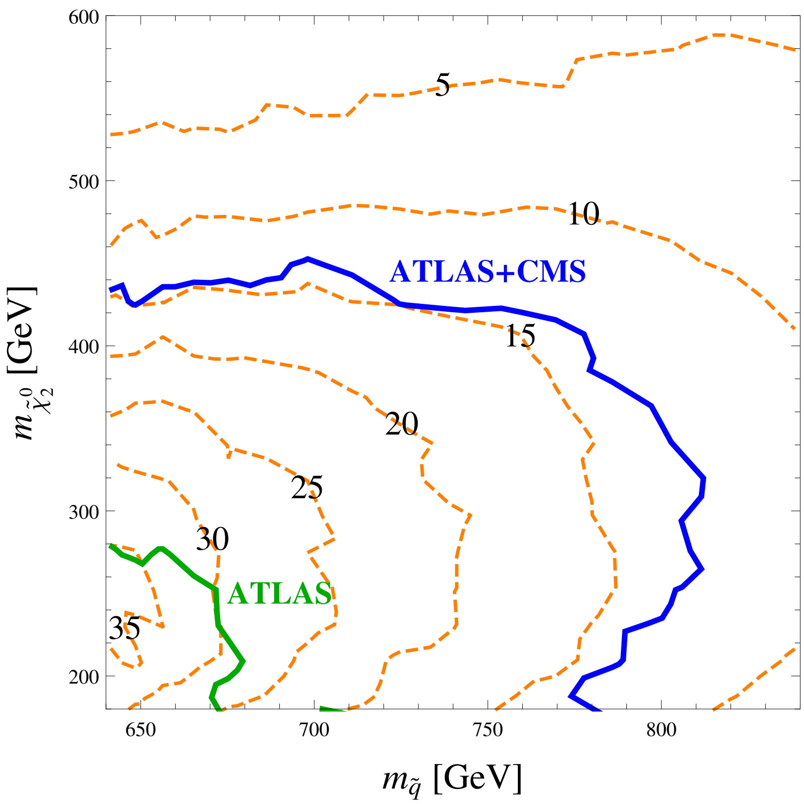

FIG. 3: Contours of signal events for the ATLAS leptonic-$Z + jets + \not{E}_T$ search in the $m_{\tilde{q}} - m_{\chi_2^0}$ plane (orange dashed curves) for our model. The corresponding exclusion limits for the ATLAS constraints alone (green curve) and the ATLAS+CMS constraints (blue curve) are shown as well.

It is interesting to investigate the conventional low energy NMSSM with heavy Majarona gluino, and compare it with our scenario, although such NMSSM cannot be realized in the usual SUSY breaking scenarios. For this purpose, we use the same signal channels and mass spectra as in Dirac gluino case. The corresponding results are presented in Fig. 4. Form this figure, we learn the following facts. Firstly, these contours for numbers of signal events have similar shape, but the absolute values are distinct. It is mainly due to the larger production rates of squark productions in conventional NMSSM. Because the cut efficiencies has no huge discrepancy for these two models, the survival event numbers are increased significantly. Secondly, for the same reason, the exclusion limits become stringent and thus requiring more compressed spectra. To be specific, for given $m_{\tilde{q}} \in [600, 900]$ GeV, $m_{\chi_2^0}$ should heavier than 520 GeV if one only includes the ATLAS constraints (see green curve in Fig. 4). Within these mass regions, the conventional NMSSM can also gives the best explanation for leptonic-Z excess, and the corresponding best fit benchmark point is given in Table IV as **bench3**. However, the CMS constraints become so stringent that almost entire parameter space in the plane is excluded. Although a few points do survive, they contributes about 11 signal events in the most optimistic case (About 1.2σ signal significance, see **bench4** in Table IV.), and their numbers are too small to draw the exclusion curve. Therefore, only the ATLAS constraints are displayed in Fig. 4. The results are similar with Ref. [15], in which the wider squark and neutralino mass ranges were studied.

IV. CONCLUSION

In the NMSSM extension with a heavy Dirac gluino and light squarks which can still keep the naturalness condition, we interpreted the 3σ leptonic-Z excess recently reported by the ATLAS Collaboration. We concentrated on light first two generation squark pair productions, and the corresponding decay chain is $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\chi}_1^0 Z$. Our basic strategy

TABLE IV: The conventional NMSSM with the same caption as Table III.

	$M_{\tilde{q}^{1,2}_{L,R}}$	$M_{\tilde{\chi}^0_1}$	$M_{\tilde{\chi}^0_2}$	All Events	Cut1	Cut2	Cut3	Cut4	Cut5	Cut6	Cut7	$N_{\rm Sig}$	$R^{\max}_{\rm ATLAS}$	$R^{\max}_{\rm ATLAS+CMS}$
bench3	738	489	602	10^5	14652	14533	13462	12876	2746	1314	1219	18.5	0.84	1.53
bench4	665	511	624	10^5	11941	11843	10959	7916	874	398	349	10.6	0.48	0.95

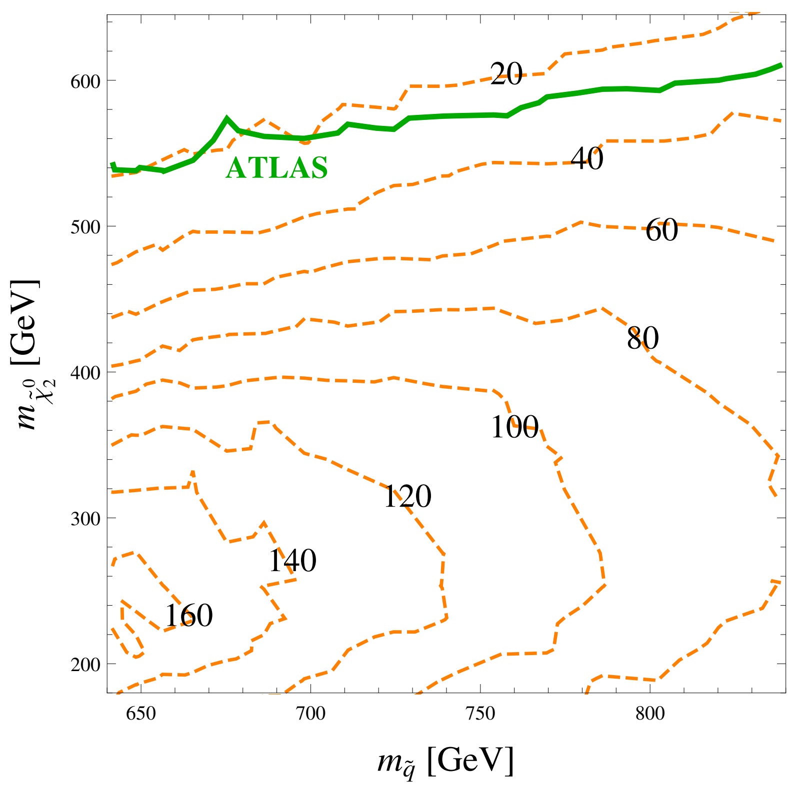

FIG. 4: The conventional NMSSM with the same caption as Fig. 3. Noticed that the ATLAS+CMS limits are too stringent to be displayed in the figure.

to produce Z boson is using a singlino-like LSP $\tilde{\chi}^0_1$ and a bino-like NLSP $\tilde{\chi}^0_2$. With specific sparticle spectra and mass splitting $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \simeq 100$ GeV, the branching ratios of decays $\tilde{q} \to q\tilde{\chi}^0_2$ and $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z$ are almost fixed to 100% in the whole parameter space. Meanwhile, to satisfy the LHC SUSY search constraints and maintain the nice supersafe feature of Dirac gluino, a relatively heavy glunio is chosen, i.e., $m_{\tilde{g}} \simeq 2.6$ TeV.

Considering the bounds from all ATLAS direct SUSY searches, the leptonic-Z excess can be fully addressed in large parameter space of our model, i.e., $m_{\tilde{q}_{1,2}} \in [650, 750]$ GeV and $m_{\tilde{\chi}^0_2} \in [200, 400]$ GeV. The **bench1** with $m_{\tilde{q}_{1,2}}$=639 GeV and $m_{\tilde{\chi}^0_2}$=398 GeV can provide the 19 signal events for the leptonic-Z excess while satisfies all the current ATLAS SUSY search constraints ($R^{\max}_{\rm ATLAS} = 0.56$).

The corresponding CMS search for exactly the same final states imposes very stringent bound on the above viable parameter space which can explain the leptonic-Z excess. The parameter space, which satisfies both the ATLAS and CMS constraints, can provide at most 15 events to the excess, which means the excess can be addressed within 1σ. The **bench2** with $m_{\tilde{q}_{1,2}}$=642 GeV and $m_{\tilde{\chi}^0_2}$=428 GeV, which contributes 15 signal events to the excess, is on the edge of the CMS exclusion curve.

For comparison, we considered the conventional low energy NMSSM with a heavy Majorana gluino and light squarks in the same parameter space. The main difference is the enhanced squark pair production cross sections from the same chirality squark pair. In the same mass regions considered in this work, we found the capacity to explain the leptonic-Z excess in both models are similar. If one only considered the ATLAS SUSY searches, a quite large viable

parameter space can give ~ 19 signal events to the Z excess, e.g., **bench3**. While the constraints from the CMS search only allow the parameter space with less than ~ 11 signal events, e.g., **bench4**.

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